

**A SIMULATION STUDY OF
CONTROL AND DISPLAY REQUIREMENTS
FOR ZERO-EXPERIENCE GENERAL AVIATION PILOTS**

by

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Purpose

To define basic human factor requirements for--

Novices (non-pilots)

Zero practice and training

Precision, curved path, accelerated, complete maneuvers

Instrument Meteorological Conditions (IMC)

Goal

To increase utility of General Aviation Airplanes by reducing training and proficiency requirements to safely access this segment of the transportation system

The purpose of this simulation study was to define the basic human factor requirements for operating an airplane in all weather conditions. The basic human factors requirements are defined herein as those for an operator who is a complete novice for airplane operations but who is assumed to have automobile driving experience. These operators thus have had no piloting experience or training of any kind. The human factor requirements are developed for a practical task which includes all of the basic maneuvers required to go from one airport to another airport in limited visibility conditions. The task was quite demanding including following a precise path with climbing and descending turns while simultaneously changing airspeed.

The ultimate goal of this research is to increase the utility of general aviation airplanes--that is, to make them a practical mode of transportation for a much larger segment of the general population. This can be accomplished by reducing the training and proficiency requirements of pilots while improving the level of safety. It is believed that advanced technologies such as fly-by-wire (or light), and head-up pictorial displays can be of much greater benefit to the general aviation pilot than to the full-time, professional pilot.

Design Principles

- **One mode of operation**
- **Pilot manually "closes the loop"**
- **Built-In safety features**

Although the simulated systems continually evolved as the tests were conducted, the evolution was guided by the principle that there would be only one mode of operation for the entire maneuver. It was believed that having multiple modes of operations would ultimately lead to "mode errors" in which the pilot would forget which mode he was operating in and make an inappropriate input. Such mode errors have proved to be catastrophic in other highly automated airplanes.

The second principle of design was that the pilot would actively be in control of the airplane. The level of augmentation required to produce satisfactory handling qualities for the novice is so high that without many changes a completely automatic system could be achieved. However, it was believed that in order to be acceptable to the public, the operator of the airplane must be in control of the airplane as it goes through the various maneuvers and not be merely a passive passenger.

Finally, the systems had to have built-in safety features. For example, the control system was designed so that the airplane could not be stalled regardless of the inputs by the pilot. In addition, the airplane could not be maneuvered to extreme pitch and roll attitudes. This prevented the airplane from being flown too fast or to high load factors. Although these safety features reduce the maneuverability of the airplane so that it cannot perform some aggressive maneuvers, this was not considered to be a real handicap for an airplane used entirely for transportation.

Decoupled Control System **(E-Z Fly)**

Throttle Lever → Airspeed

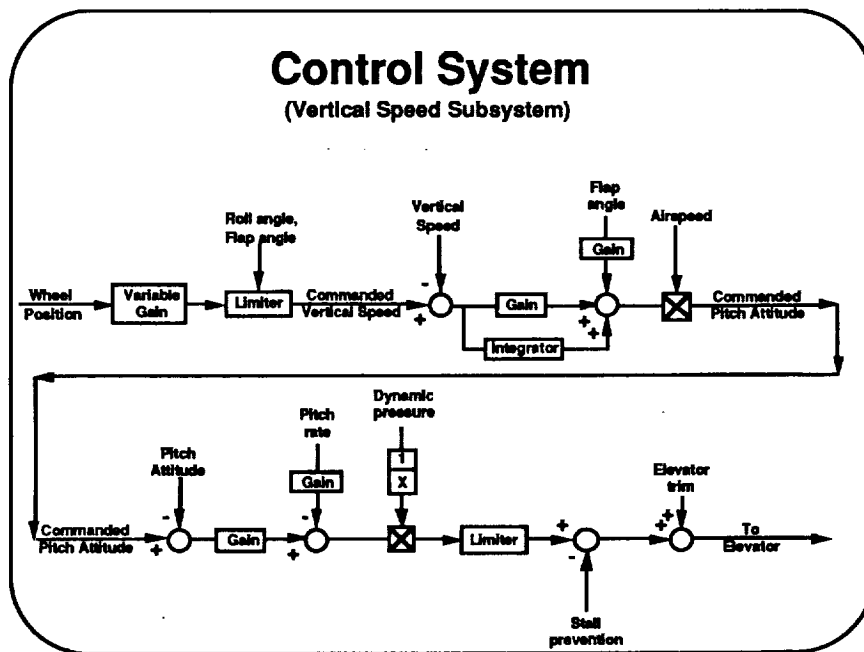
Long. Wheel → Vertical Speed

Lat. Wheel → Heading Rate

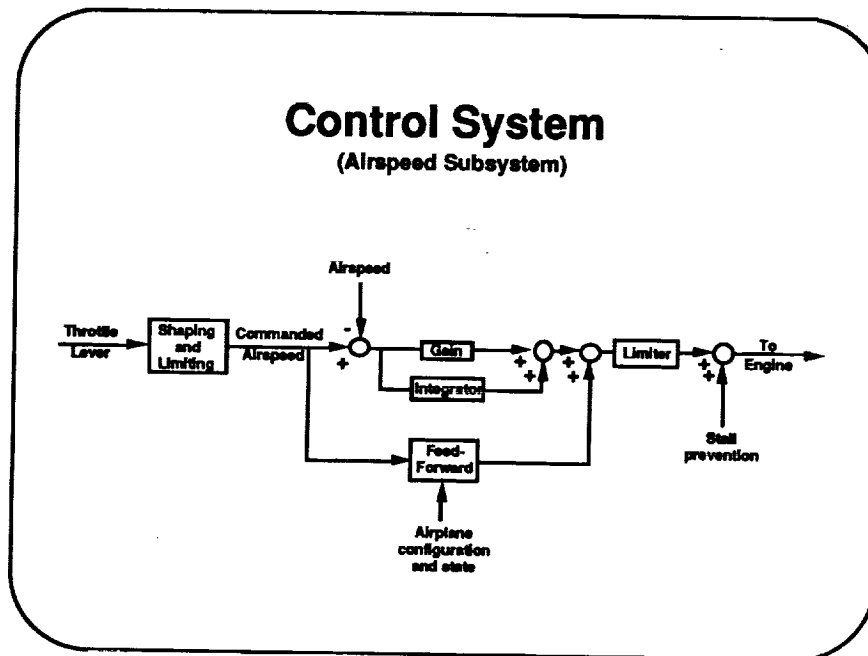
R. Pedals → Sideslip

The E-Z Fly control system was designed to "decoupled" the airplane responses as shown here. The three primary cockpit controls (throttle, longitudinal wheel, and lateral wheel) individually and separately determine the three primary parameters (airspeed, vertical speed, and heading rate) needed to get from one point in space to another. In a conventional airplane the airspeed, vertical speed, and heading rate can all respond simultaneously to a single input on one of the cockpit controls—that is, the responses are coupled. The pilot must learn to suppress the unwanted responses in order to get the airplane to respond the way he wants it to. It is this coupling that makes an airplane hard to learn to fly for a novice.

The fourth cockpit control, the rudder pedals, was used to control the sideslip angle in the E-Z Fly control system. Ordinarily, the rudder pedals were left in the center position where they commanded a zero sideslip angle so that turns with the lateral wheel were naturally coordinated. However, in cross-wind conditions the rudder pedals could be used to align the nose of the airplane with the ground track.



The E-Z Fly control system would probably require a fly-by-wire (or light) control system. The block diagram for the longitudinal-wheel-position-to-vertical speed subsystem is shown here. The wheel position was fed through a gain (which was decreased on final approach to provide fine control) and a limiter which kept the system from commanding a vertical speed the airplane could not sustain indefinitely. The heart of the control system was a simple proportional plus integral controller which was scheduled according to the airspeed and dynamic pressure. Pitch attitude and pitch rate were used to stabilize the system. Finally, a stall prevention feature based on angle of attack was added as a back-up to provide nose-down elevator. Ordinarily, this feature was never actuated because of the limiter on the commanded vertical speed mentioned earlier. However, the stall prevention feature was added insurance for extreme combinations of low airspeeds and large roll angles with the flaps and landing gear extended. These extreme conditions were never encountered if the pilot followed the pictorial head-up display.

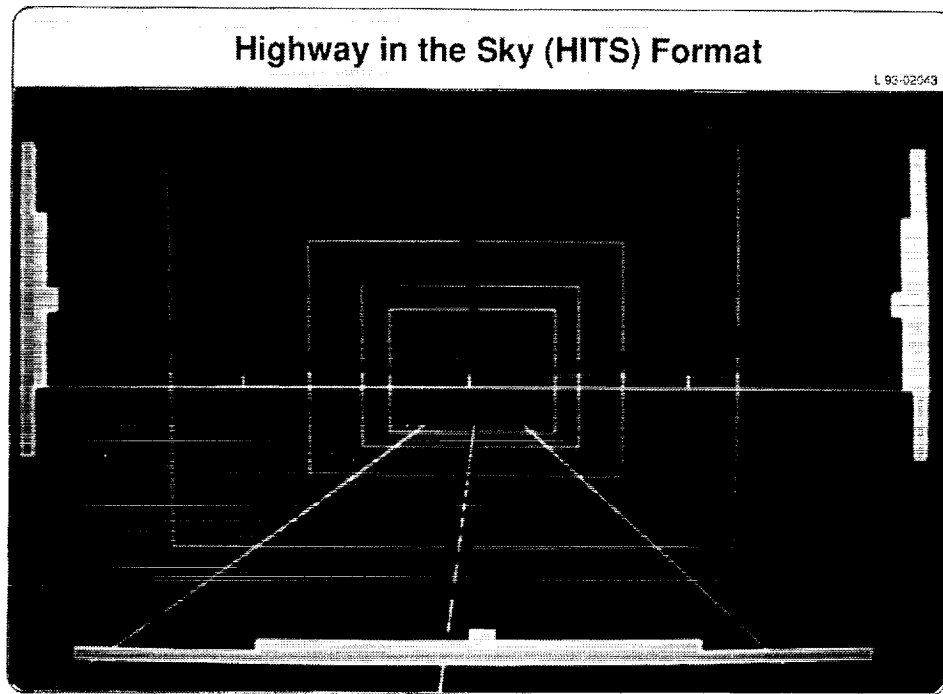


The block diagram for the second major component of the E-Z Fly control system is shown here. The average position of the throttle levers in the cockpit commanded the desired airspeed after passing through a shaping and limiting filter. This filter prevented the system from commanding unrealistic airspeeds which the airplane could not sustain safely. The commanded airspeed was directed through a feed-forward loop which defined a nominal throttle position as a function of the airplane configuration (flap and landing gear positions) and airplane state (vertical speed, roll attitude, and sideslip angle). The airspeed error was fed through a proportional path and an integral path. The integrator, of course, assured that the airspeed error was zero after the transients had died out. The final limiter function had a "sliding window" which allowed $\pm 20\%$ deviation of the throttle position from the nominal feed-forward throttle position. This "sliding window" was added to limit the amount of engine activity when large changes were made in the commanded airspeed. As a back-up, a stall prevention term driven by the angle of attack was added to commanded throttle position. As with stall prevention term for the vertical speed subsystem, this term was not needed except for extreme combinations of airplane configuration and state. These extreme conditions could not exist unless the airplane was completely off the desired trajectory.

Additional Control System Features

- **Lateral wheel used to taxi**
- **Automatic control force trim**
- **Variable gain on final approach**

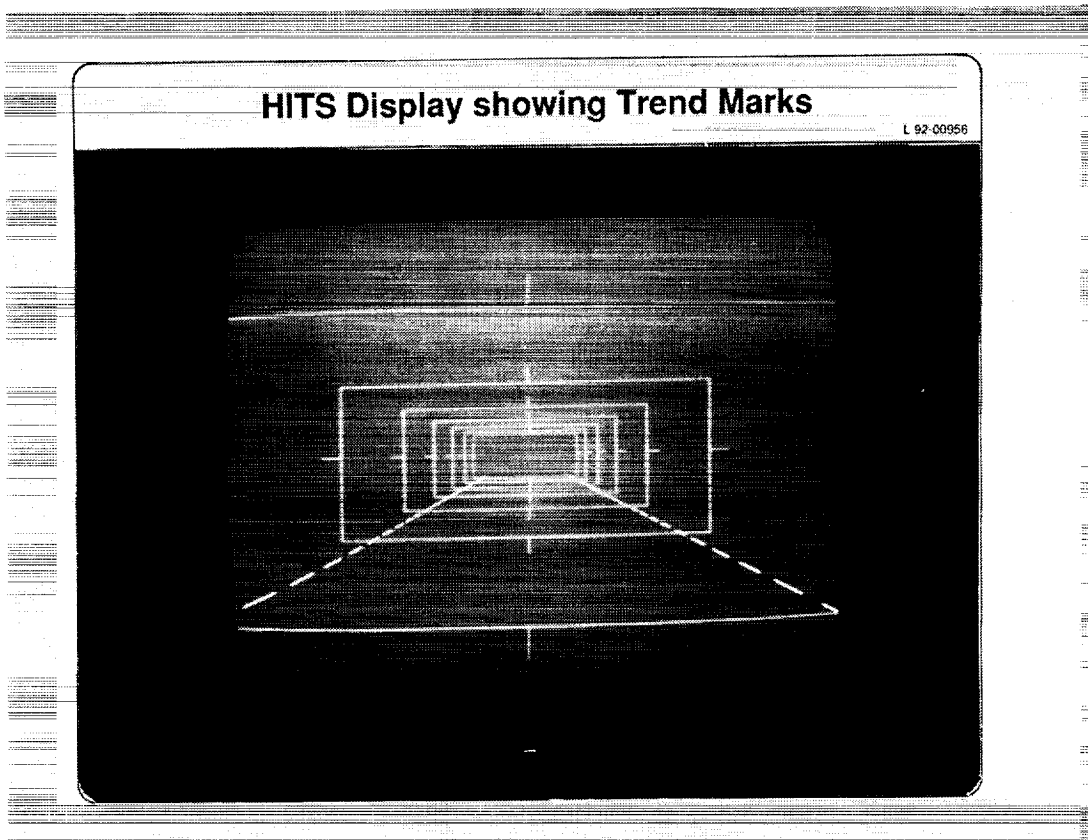
Some additional features of the control system which do not appear on the previous slides are shown on this slide. The lateral wheel, rather than the rudder pedals, was used to steer the nose wheel on the ground. Whenever the airplane was on the ground the loop was opened in the usual lateral-wheel-to-roll-angle control system. Thus, the airplane was turned right or left by using the lateral wheel regardless of whether the airplane was in the air or on the ground. The second feature, automatic control force trim, was very helpful to the novices especially on their first simulated flight. Whenever there was a force on the longitudinal or lateral wheel, the control force was automatically reduced to a low level over a period of time. The novice pilots were completely unfamiliar with the concept of control force trim and almost never used the electric trim switch mounted on the control wheel. Without the automatic control force trim the novice test subjects often flew for long periods of time with steady control forces. These forces made it difficult to control the airplane precisely. The final feature was an automatic reduction of the gains on the longitudinal and lateral wheel during the final approach. The guidance (highway) was narrowing on final approach and unless the gains were reduced on the control wheel, the airplane appeared to be overly sensitive.



The second element of the E-Z Fly system was the Highway In The Sky (HITS). Although there were several variations of HITS, the basic format of this pictorial display is shown in this slide. The "surface" of the highway is marked by a solid white stripe on each side and a striped white line down the center as shown in the lower center of the slide. This highway was fixed in space and the airplane was flown above and past the highway. To provide increased vertical guidance green boxes were drawn on the road as shown. The green boxes and white stripes were ordinarily drawn about 6000 feet in the distance and had a nominal width of 1000 feet. As the airplane passed by a box or a section of the road, that box or section would pass out of view and a new box and road section would be added on at the far end of the road. This prevented the clutter of the display which would have resulted if the road was extended to the final destination. The 6000 feet of highway visible still provided some anticipation of when turns would have to be made in the future. The boxes had small gaps in the middle of each side which were used as aiming points for the red "trend mark." (Only the vertical trend marks are shown on the above slide).

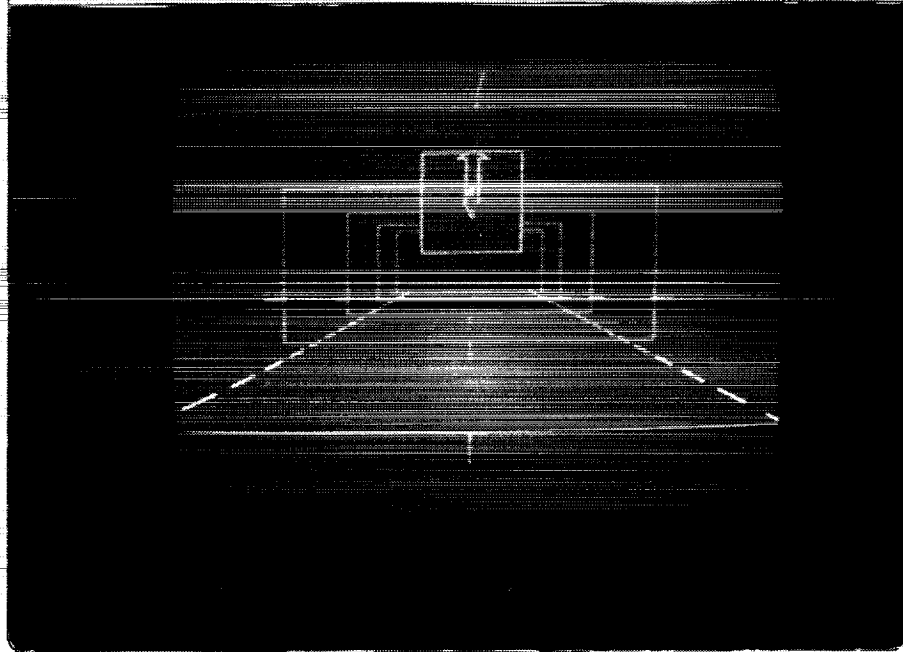
A white horizon line was drawn across the display. Small vertical tick marks were placed every 10° of heading.

Finally, fixed green reference guides were added on either side and at the bottom of the display. The guides were fixed on screen regardless of the airplane maneuvering. They were ordinarily adjusted for each pilot so that they were at the very edge of his field of view. The guides on the sides could be used with the white horizon line to gauge pitch attitude. The guide at the bottom could be used to help in lateral steering.



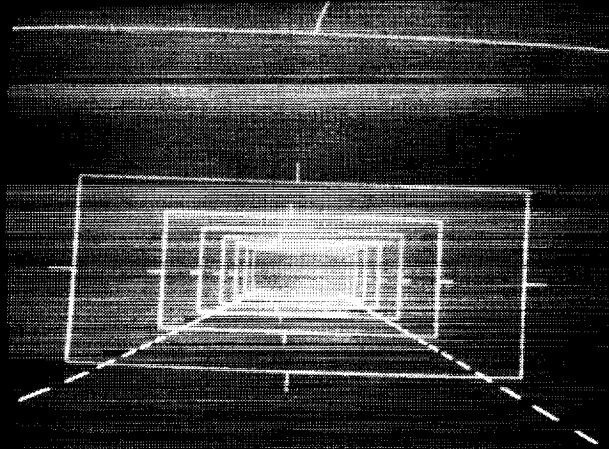
The vertical and lateral trend marks are shown in the center of the boxes of an earlier version of HITS in the above slide. The trend marks are used to provide linear rate information relative to highway. The perspective of the boxes and the lane stripes relative to one another seemed to provide adequate position guidance. However, the test subjects had trouble anticipating where they were going to be in the future because they had to mentally differentiate the time rate of change of the perspective of the highway. The trend marks helped by indicating where the airplane would pass through a given box if the controls were held in their present position. That is, an imaginary horizontal line drawn between the two red marks on the sides of the boxes would intersect a vertical line drawn between the red marks on the top and bottom of the boxes at the point the airplane trajectory would intersect the plane of the box. The trend marks responded very quickly to control inputs and thus gave much more rapid feedback than did the more slowly changing perspective of the pictorial highway.

Excess Downward Velocity

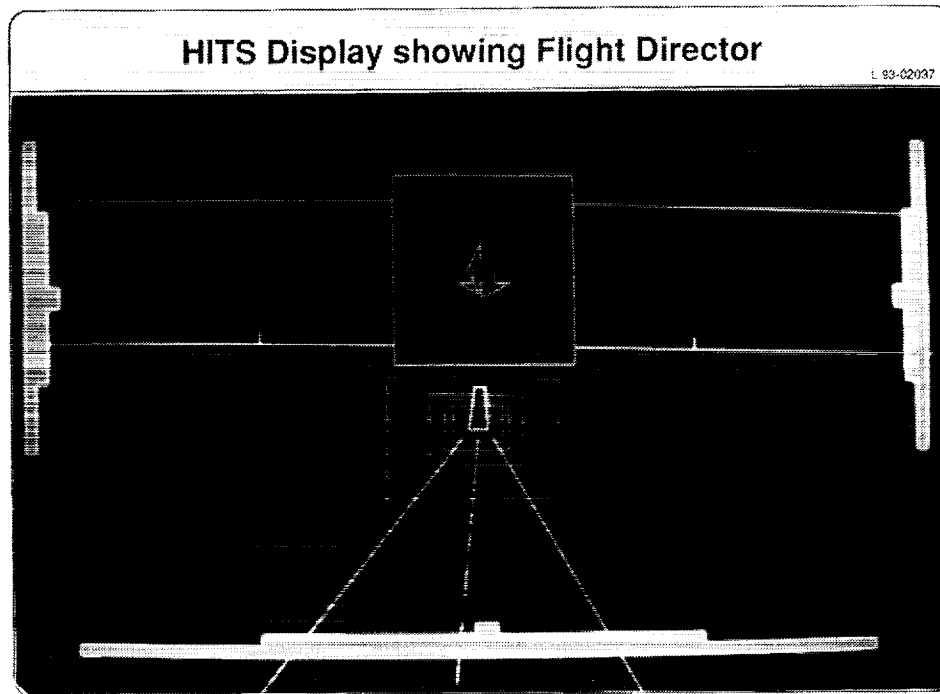


This slide depicts the situation in which the airplane is in the correct position relative to the highway (the boxes are centered), but there is a downward velocity (the trend marks are progressively lower on more distant boxes). Also shown on this slide is the so-called "flight director" arrows in the white "sign" box. In this situation, the flight director arrows are indicating the pilot should pull up to arrest the downward velocity. In most situations where the pilot is properly following the HITS, the square white box and flight director arrows are removed to prevent clutter and provide a more intuitive display. More will be said about the flight director arrows later.

Left-ward Lateral Velocity



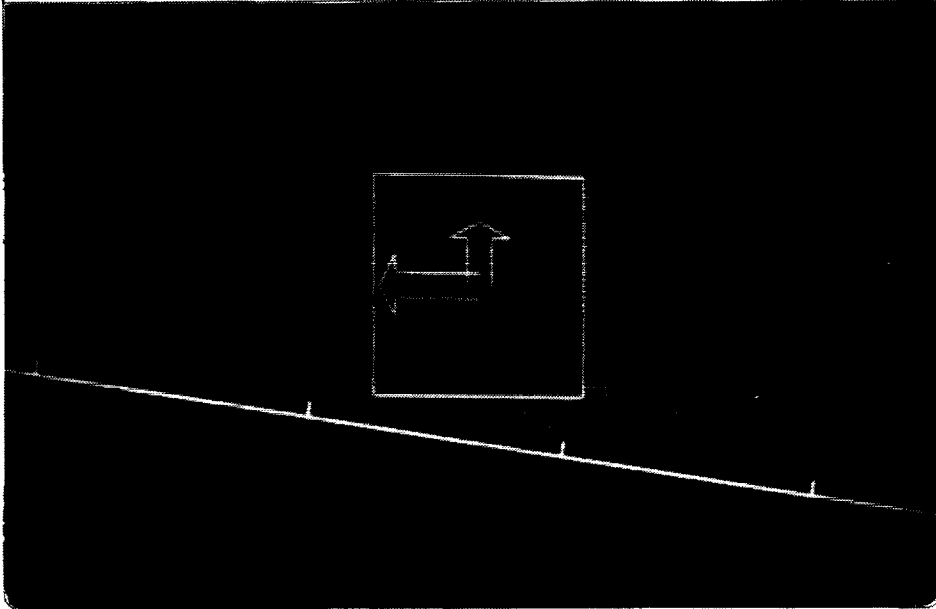
This slide shows what the display looks like when the airplane is on the centerline but is going to the left. As indicated by the lateral trend marks the present trajectory of the airplane will take the airplane off the side of the more distant boxes. The lateral trend marks were much more sensitive to lateral wheel inputs than the vertical trend marks were to longitudinal wheel inputs. This difference in sensitivity is due to fundamental physical differences in the airplane's responses in the two axes.



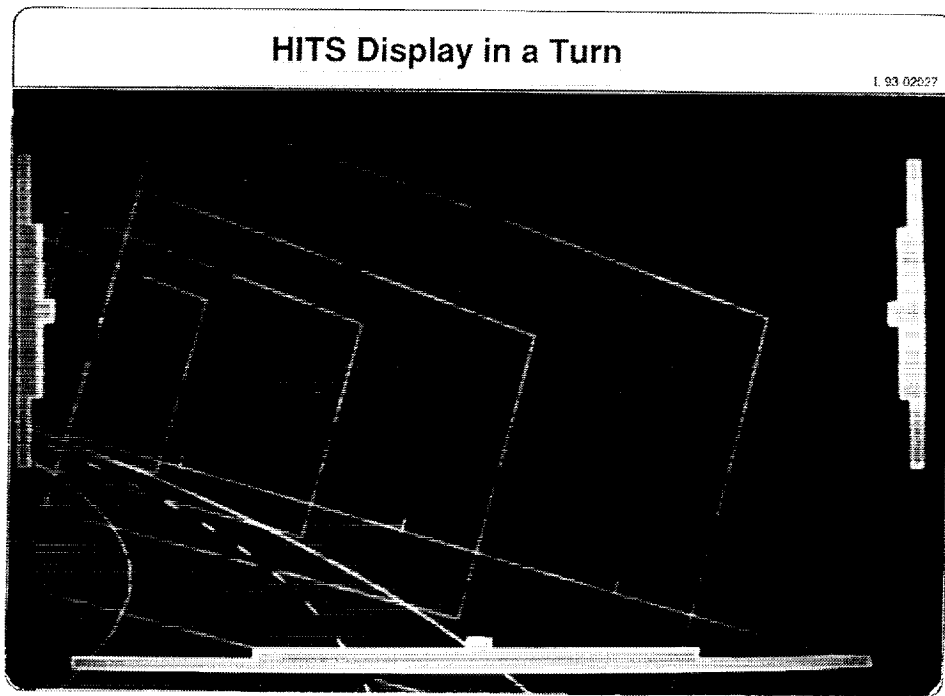
This slide shows the flight director arrows indicating that a slight push of the longitudinal wheel and left turn of the lateral wheel is needed. The flight director arrows were ordinarily not displayed when the pilot was close to the nominal trajectory. However, in this study the flight director arrows were used to indicate when it was time to rotate the airplane for takeoff and when to flare the airplane for landing. The flight director arrows usually disappeared shortly after takeoff when the pilot flew near the nominal trajectory. They remained off until the final approach as shown in the above slide. They were programmed to come on during the final approach even if the pilot was very close to the nominal trajectory. This was done because the vertical arrow was needed for the flare and it would probably have been too distracting for the arrows to appear suddenly at the flare point.

Flight Director Arrows When Completely off the HITS Trajectory

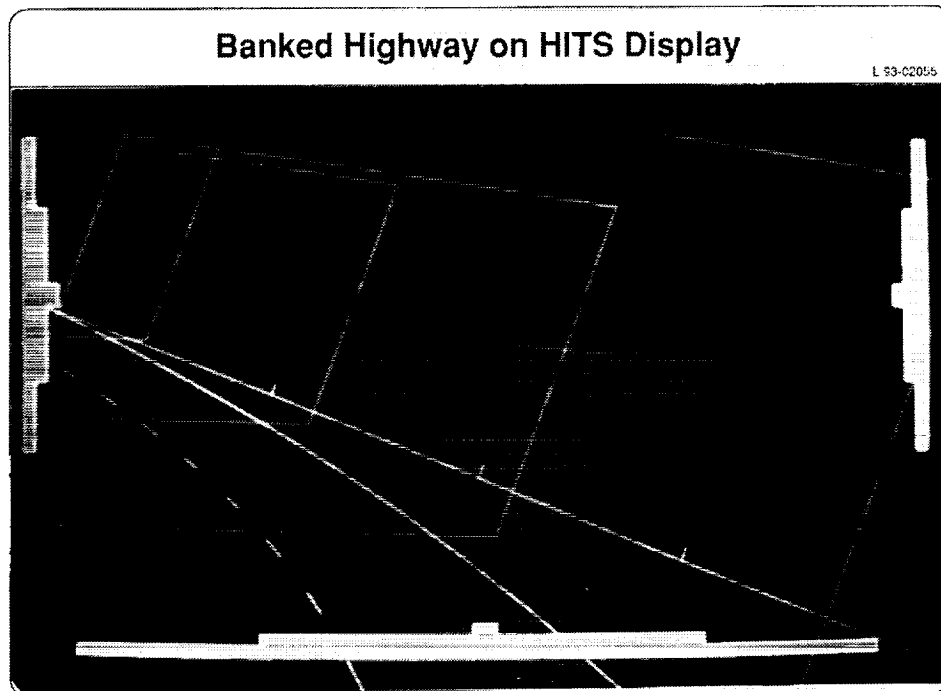
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In addition to the rotation and the flare, the flight director arrows were needed when the pilot flew so far off the HITS trajectory that the highway could no longer be seen. This situation is depicted in the above slide where the pilot needs to pull up and turn to the left to re-acquire the pictorial part of the HITS display. A few of the novice pilots flew off highway during the first turn and had to use the flight director arrows to get back to the highway. In the majority of the cases, however, the test subjects always maintained visual contact with the pictorial highway.



A sample of what the display looks like in a climbing turn is shown in the above slide. The "surface" of the highway was level in the turns and the boxes also remained vertically oriented (no bank). The airplane, of course, had to be banked to execute the turn; and this airplane bank can be seen by the angle between the fixed reference guide at the bottom of the display and either the horizon line or the sides of the boxes. In the turn, the geometry is such that the center of the reference guide does not line up with the center of the highway as it does in the straight segments. It appeared that placing the center of the reference guide on the outside (solid) highway stripe as shown above placed the airplane on a good trajectory. However, this technique had to be learned and thus did not satisfy the original goal of making the display completely intuitive.



A limited number of runs were flown with a display in which the highway "surface" and the tops and bottoms of the boxes were banked as shown in the above slide. It was hoped this would be more intuitive than the unbanked display and that the reference guide could be aligned with the bottom (or top) of the boxes. However, most of the test subjects preferred the original display. The boxes appeared distorted and the transition from the straight segments to the turns and vice versa were confusing. It was discovered that the perspective in the climbing and descending turns was such that the bank of the highway had to be less than that of the airplane if the reference guide was to appear parallel to the bottom (or top) of the boxes.

Test Subjects

Subject	Piloting Experience	Occupation	Age	Sex
1	0 hours	Engineer	24	Female
2	0 hours	Engineering Graduate Student	23	Female
3	8700 hours	Research Pilot	40	Male
4	0 hours	Secretary	29	Female
5	0 hours	Business Co-Op	20	Female
6	0 hours	Graphics Co-Op	24	Male
7	0 hours	Secretary	36	Female
8	800 hours	Engineer	43	Male
9	0 hours	Engineering Graduate Student	29	Male
10	6300 hours	Research Pilot	52	Male
11	800 hours	Engineer	45	Male
12	0 hours	Engineer	49	Male
13	0 hours	Engineering Co-Op	21	Male
14	0 hours	Library Science Co-Op	25	Female
15	0 hours	Engineering Co-Op	19	Male
16	400 hours	Engineer	45	Male
17	0 hours	Engineering Co-Op	19	Male
18	0 hours	Engineering Co-Op	20	Female

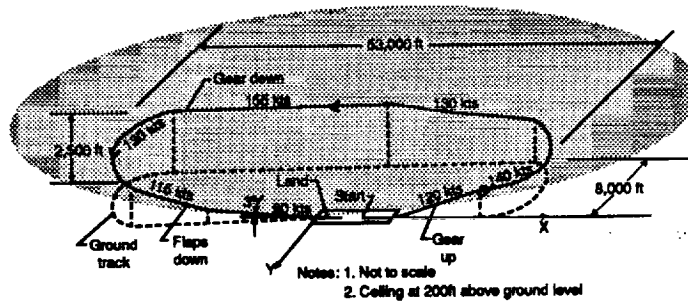
A wide variety of tests subjects was used in this study as can be seen from this slide. Only ten of the test subjects flew the initial series of test with a systematic set of research variables. The other eight test subjects flew only selected configurations such as the banked highway display.

Test Subject Summary

- **Piloting Experience**
 - 5 with at least some experience**
 - 13 without any experience**
- **Background**
 - 5 with non-technical backgrounds**
 - 13 with technical backgrounds**
- **Sex**
 - 7 females**
 - 11 males**
- **Age**
 - 19 to 52 years old**
 - 31 years average age**

Although all kinds of test subjects were used, most of the test subjects had no prior piloting experience. Since the test subjects were selected from the staff at the Langley Research Center most of the test subjects had a technical background. Also the test subjects were predominantly males. Only five of the test subjects were over 40 years old, and the average age was 31 years.

Maneuver



The same test maneuver was used for all the test subjects. The maneuver consisted of a racetrack-shaped maneuver including a takeoff and a landing. There were seven segments, each of which was flown at a different airspeed. Since the maneuver was only about 10 minutes long, the airplane was accelerating from one airspeed to another most of the time. The maneuver included complex tasks such as precision climbing (or descending) turns while accelerating from one airspeed to another. In addition, the landing gear and flaps were exercised. Perhaps the most significant factor was that most of the maneuver was conducted in reduced visibility conditions. That is, most of the maneuver was conducted above the simulated ceiling height of 200 feet.

Research Variables

- **Control System (on or off)**
- **Automatic control force trim (on or off)**
- **Head-up or Head-down display**
- **Winds and turbulence**
- **Display format**
 - Trend marks**
 - Reference guides**
 - Banked turns**

Several research variables were investigated as shown in this slide. Each of the variables was evaluated to see if it was necessary or helpful for the test subjects. The intent was to establish the minimum features to safely conduct the maneuvers.

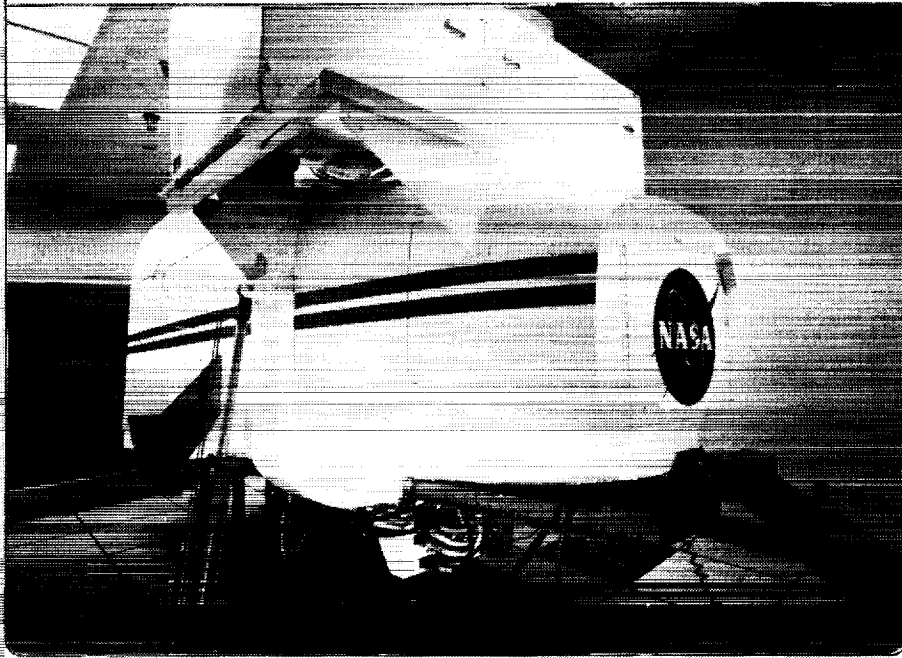
Procedure

- **Short briefing of test subjects~30 minutes**
- **Data taken on first run--no practice**
- **Limited number of total runs**
 - Repeat of baseline configuration to track learning curve**
 - One run with each research variable**

The test subjects were given a short briefing to explain what the overall objectives of the research program were and to explain the fundamentals of what their task would be. The cockpit controls were identified and photographs of the display format were explained. After this introduction the tests subjects were allowed to fly the maneuver with almost no coaching from the researcher. For example, if the test subject failed to raise the landing gear or made some other obvious mistake this might be point out. But in general the researcher did not coach the subjects on when and how much control input to make. A limited number of runs was allowed for each test subject because they were learning so quickly. The first run(s) was considered to be the most important because the test subject's natural instincts readily came out then.

The default configuration of the simulation was: 1) E-Z Fly control system on, 2) Head-up pictorial display, 3) Automatic control force trim on, 4) Calm air conditions, 5) Vertical trend marks on, 6) Reference guides off, and 7) Unbanked highway turns. This was the first configuration flown by most of the test subjects. Then on alternate runs one of the research variables was altered. After one non-default variable conditions was tested, the default configuration was flown again. Thus, the default configuration was flown every other run throughout the sessions. This made it possible to track the test subjects' learning curves which were very steep because as mentioned earlier no prior training or practice was allowed. It also allowed the test subjects to directly compare one of the research variables to the default configuration.

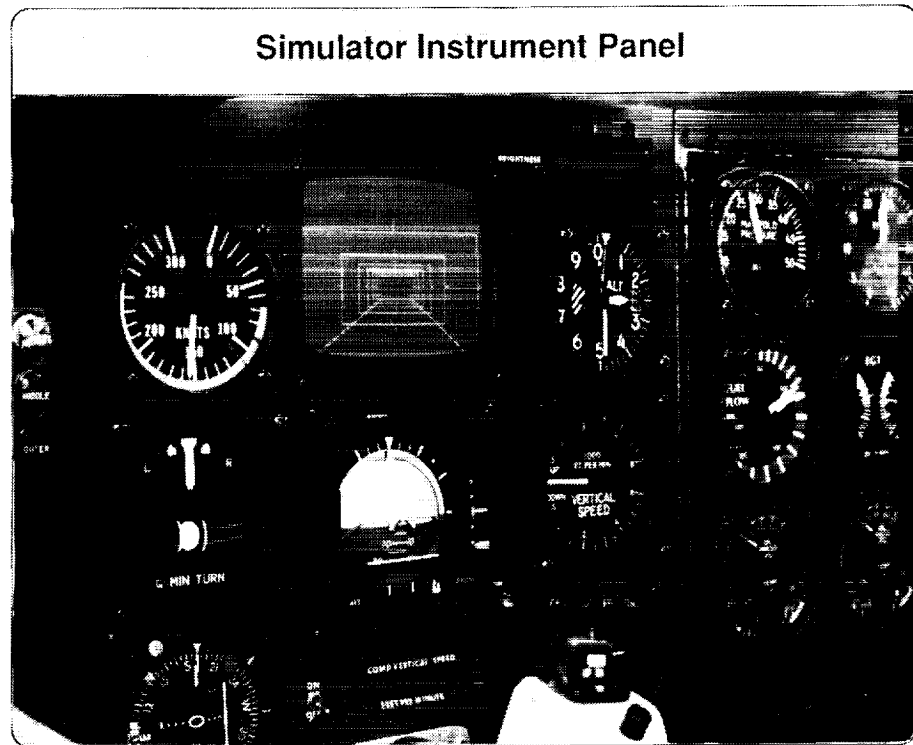
Simulator Exterior



The Langley General Aviation Simulator was used in these tests. The simulation cockpit was mounted on a 3 DOF motion base which provided limited motion cues in pitch, roll, and heave. Of course, the equations of motion (and the visual system) had 6 degrees of freedom.



The cockpit was equipped with a computer generated image (CGI) visual scene out the front window. For the Head-up configuration, the line drawings of the HITS display were overlaid on the CGI image with a total field of view of about 38° laterally by 20° vertically. The cockpit also had a hydraulically-actuated control loader system to provide programmable force feel characteristics. Engine and windstream sounds were simulated by a series of speakers around the cockpit. A conventional instrument panel with mechanical displays was provided, but the test subjects almost never referred to these instruments.



The instrument panel was modified as shown to evaluate the HITS in a head-down arrangement. A 5-inch black and white television monitor was mounted in the top center of the instrument panel. Unfortunately, the monitor had poor resolution. And because the monitor had a black and white format, the color distinctions of the HITS display could not be seen. Although the physical field of view of the monitor was small, the picture on the monitor represented a substantially larger field of view than did the head-up configuration. In the head-down configuration the simulated field of view was about 43° laterally by 25° vertically. This compares favorably to the 36° by 20° field of view in the head-up configuration.

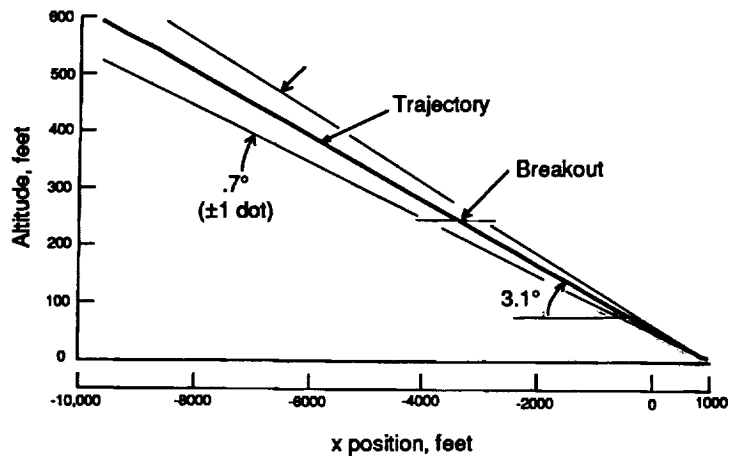
Video

(4 minutes)

The video is a recording of the head-up visual scene during a maneuver flown by an experienced test subject. Selected portions of the maneuver are shown, including most of the final approach and landing.

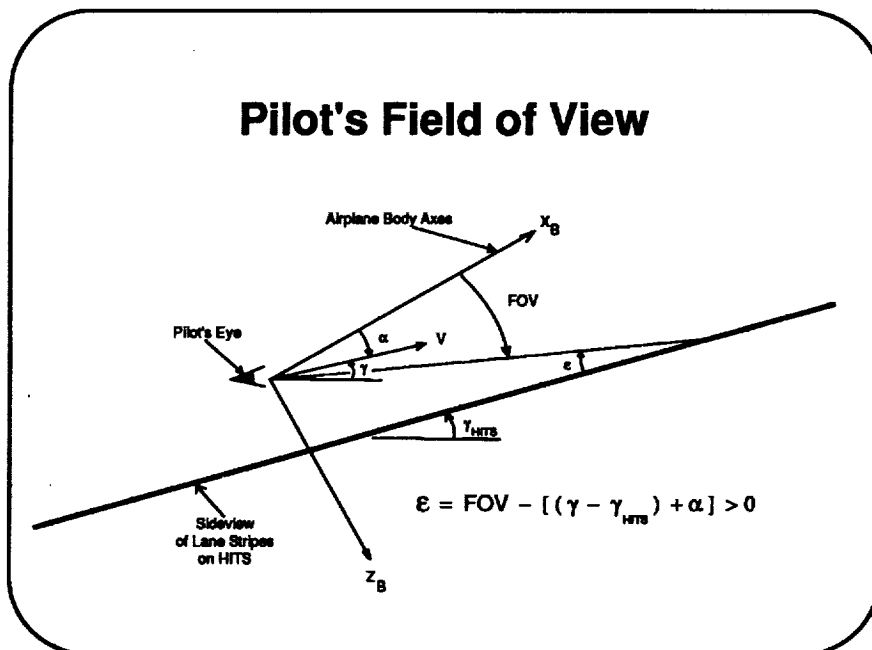
First Trajectory by Zero-Experience Test Subject

(Compared to standard ILS glideslope accuracy)

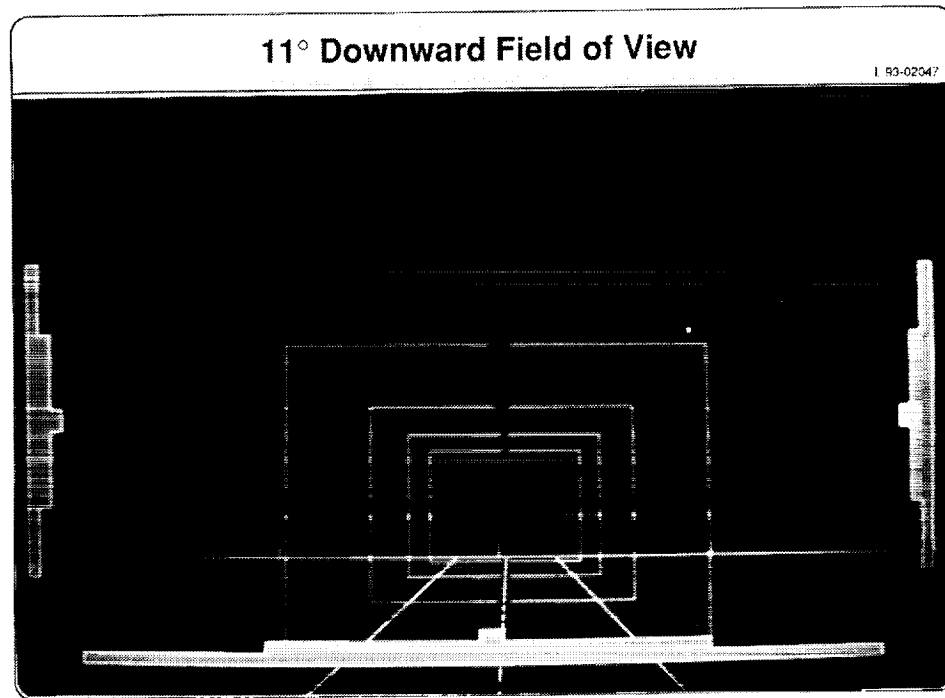


This slide shows the actual final approach trajectory flown by one of the zero-experience test subjects on his very first maneuver. The trajectory was flown with the default configuration (E-Z Fly control system and the head-up pictorial HITS display). For comparison purposes only a ± 1 dot deviation on a standard ILS Instrument is superimposed on the trajectory. The test subject was not flying an ILS approach. It is apparent that the test subject was able to very precisely control the flight path.

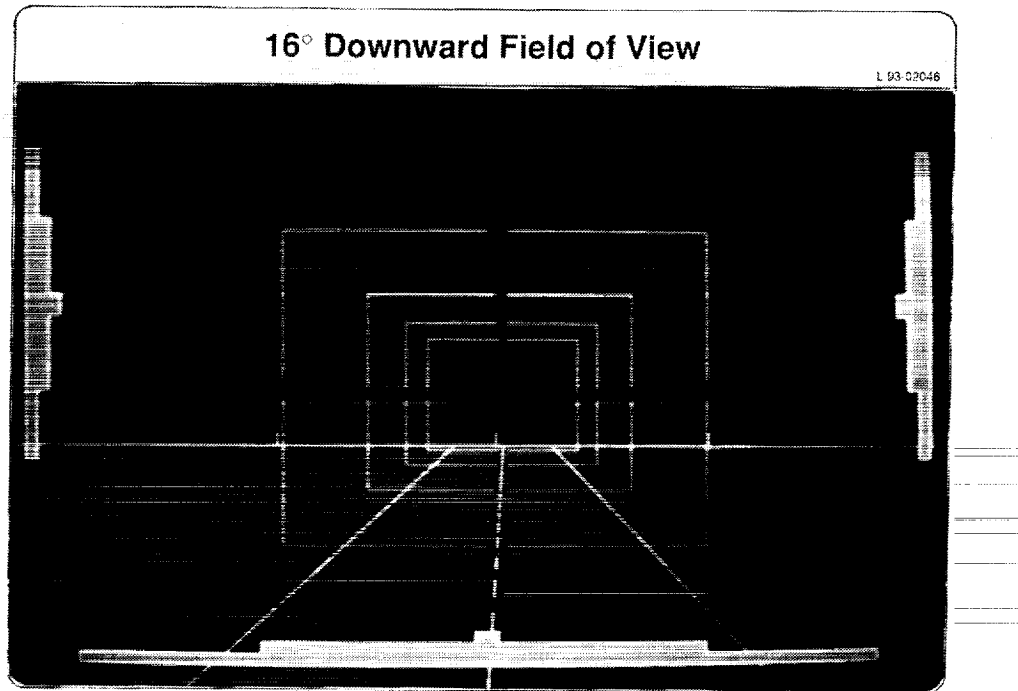
Pilot's Field of View



The amount of downward visibility (the angle FOV in the above slide) was critical to optimum performance. In order to see the lane stripes and the bottoms of the boxes the visual intercept angle, ϵ , had to be positive. In fact, the intercept angle has to be reasonably large, 3 or 4 degrees, if the highway is to be seen a reasonable distance ahead of the airplane. From the above formula it can be seen that if the airplane is climbing more steeply than the HITS path, $(\gamma - \gamma_{HITS})$ positive, or the angle of attack, α , is large; the intercept angle will be small. In this situation, the downward visibility, FOV, must be large. Immediately after takeoff when the airplane was climbing steeply at a low airspeed, the downward visibility was limited. This proved to be a critical time since the test subjects were not used to the display at all on their first run.



This slide illustrates the view for the default value of 11° for the downward field of view. The picture was taken on an ascending straight path. The fact that the HITS path is ascending can be ascertained by the fact that the vanishing point of the lane stripes is above the horizon.



This picture was taken for same identical conditions as the previous slide except that downward field of view has been increased by 5° to 16°. The lane stripes are much more evident. The lane stripes can be aligned with the reference guide especially in the turns.

Results

- 100% of test subjects were able to complete IFR maneuver on first attempt without training or practice
- Automatic control force trim is very desirable
- Control system and display are synergistic
- Head-up display strongly preferred
- Downward field of view is critical
- Vertical trend marks are very helpful
- Lateral trend marks are helpful but extremely sensitive
- Reference guides are beneficial
- Turbulence and crosswinds are manageable
- Banked turn display was not helpful

Some of the results of this study are summarized in this slide. The latest tests were the most successful to date. All of the test subjects were able to complete the entire maneuver on the first attempt without training or practice. The control system and display seem to complement one another, and the novices need to have both of them. Automatic control force trim made it possible to more precisely control the airplane because most of the novice test subjects never used the manual electric trim switch. The head-up display was universally preferred over the head-down display, but the comparison was not really fair because the head-down had poor resolution and no color. The downward field of view was critical especially in the first climbing turn. The trend marks were very helpful to the novices probably because of the immediate feedback they provided for pilot inputs. However, the lateral trend marks were overly sensitive to small inputs. The reference guides were also useful in helping to point the airplane in the proper direction. Turbulence and crosswinds degraded piloting performance, but caused no real problems. Most of the test subjects were able to track the HITS path even in the presence of a 14 knot crosswind. They usually recognized the misalignment of the airplane nose with HITS path, but this did not alter their basic flying technique. A short evaluation of a HITS with a banked roadway was made. Although it was hoped that using the angle of the bottom of the boxes to align the reference guides would be helpful, the banked turns were in general harder to fly than the basic unbanked display. The apparent distortion of the boxes and the reduction of vertical direction cues outweighed any improvement from the increased roll attitude guidance.

